AMBIGUITIES IN GLOBAL OPTICAL FLOW: TUNING IN TO SPEED AND ALTITUDE CHANGES

Darby L. Patrick, John M. Flach, & Paul F. Jacques
Department of Psychology, Wright State University, Dayton, OH USA

This paper reports results from an experiment in which participants were flown through a flight trajectory in which speed, altitude, or a combination of the two were smoothly changed. The participants' task was to estimate the magnitude of any changes in speed and altitude. The results showed that changes in altitude affected judgments of speed and that changes in speed affected judgments of altitude in a direction that was consistent with the hypothesis that observers used Global Optical Flow Rate (GOFR) as an index of both speed and altitude change. However, the magnitudes of the effects were smaller than would be expected if judgments were simply proportional to GOFR. An observer model is proposed that accounts for the magnitude of the effects in this experiment and that can be tuned to predict the wide range of effects that have been reported in the literature on GOFR. In this model, the cross-talk between altitude change and speed change is a function of the observer gain. When observer gain is high, then there is little cross-talk. When observer gain is low, then there is greater cross-talk. The model predicts judgments proportional to GOFR when the observer gain is unity.

Introduction

Warren (1982) introduced the construct of Global Optical Flow Rate (GOFR) as a hypothesis to explain altitude dependencies that had been noted in reports of judgments about the speed of self-motion. This construct was derived as a logical extension of an analytical specification of the optical flow field derived by Gibson, Olum, and Rosenblatt (1955). Warren (1982) noted that the expression for angular velocity of any point in the optical flow field could be parsed into three independent components. Two of these components (azimuth and declination) were a function of the specific local position of a texture element. The third factor was a "global" multiplier that is reflected in the flow rate of every texture element in the field, independent of its location on the texture surface. It is this third component, the ratio of the speed at which the observer is moving to the distance to the texture surface, that Warren defined as GOFR.

Thus, the global rate at which texture flows in the visual field of a moving observer (GOFR) is directly proportional to the speed of self-motion and inversely proportional to the distance to the textured surface. This distance to the textured surface is typically specified as altitude or eye-height. For an observer whose distance from the textured surface is relatively constant (e.g., during bi-pedal locomotion or when driving a car), GOFR can provide a reliable index of the speed of self-motion. However, when both speed and distance are varying together, as is often the case in flying, then there is a potential for ambiguity. That is, it may be difficult for an observer to differentiate the extent to which a change in GOFR is due to a change in speed or to a change in altitude.

To the extent that this ambiguity leads to misjudgments about either speed or altitude, there may be important implications for aviation safety. This would be particularly true for situations where an aircraft was operating near the edges of the flight envelop (e.g., low altitude and/or low speeds).

Since Warren's (1982) original hypothesis, numerous studies have examined speed judgments as a function of GOFR (e.g., Ballard, Roach, & Dyre, 1998; Dyre, 1997; Larish & Flach, 1990; Owen & Warren, 1987; Owen, Warren, Jensen, Mangold & Hettinger, 1981). Consistent with Warren's hypothesis the studies all show that altitude has an impact on judgments of the speed of self-motion in a direction consistent with changes in GOFR. That is, for a given speed of movement, judged speed tended to decrease as altitude increased.

An Experiment

This experiment was designed to further evaluate Warren's GOFR hypothesis. Observers flew a series of trajectories where altitude, speed, or both changed smoothly over the course of the trajectory. At the end of the trajectory the observers were asked to estimate the magnitude of change in speed and altitude that they experienced.

Methods

Design. Each observer completed three blocks of 25 trials. The 25 trials were created by the factorial combination of five levels of speed change with five levels of altitude change as shown in Table 1. Altitude and speed changes are specified in the margins of Table 1 and the resulting changes in GOFR are shown in the body of the table. The first

Table 1. Changes in GOFR as a function of Speed and Altitude Manipulations
.

	% Change in Altitude				
% Change in Speed	+33(800)	+17(700)	0(600)	-17(600)	-33(400)
+33(240)	0(0.506)	+14(0.579)	+33(0.675)	+60(0,810)	+100(1.013)
+17(210)	-12(0.444)	0(0.506)	+17(0,591)	+40(0.709)	+75(0.886)
0(180)	-25(0.380)	-14(0.434)	0(0.506)	+20(0.608)	+50(0.760)
-17(150)	-38(0.317)	-29(0.361)	-17(0.422)	0(0.506)	+25(0.633)
-33(120)	-50(0.253)	-43(0.289)	-33(0.338)	-20(0.405)	0(0.506)

number for each entry shows the percentage change over the trajectory. The numbers in parentheses indicate the final speed (kts), altitude (ft), or GOFR (eyeheights/s) at the end of the trajectory. All trials began at an altitude of 600 ft. with an initial speed of 180 kts. An additional variable was the flight direction. On one block the flight trajectory approached and flew over a simulated runway (Parallel). On another block the flight trajectory crossed the runway (Perpendicular). The flight direction had implications for the type of texture that was in view during the flight. For the Parallel Direction the splaying of the edges of the runway provided a potentially salient source of information about altitude change not available for the Perpendicular Direction (Flach, Hagen, & Larish, 1992; Flach, Warren, Garness, Kelly, & Stanard, 1997). Each observer participated in three blocks of trials. In the first block, half of the observers flew the Parallel Direction and the other half flew the Perpendicular Direction. This block was used to let subjects experience the full range of stimuli, providing a context for the magnitude judgments. The second and third blocks were treated as experimental trials. Half of the people in each training group flew the Parallel Direction first and the other half began with the Perpendicular Direction. The result is that there were four different orders reflecting the type of training crossed with the direction for the first experimental block. The dependent measures were magnitude estimates in which the observers specified their judgments of the degree of change in speed and altitude on a scale from –100 to +100..

Participants. Six women and ten men participated in this study. Ages ranged from 18 to 55. None of the participants had a pilot's license, although one of the participants had approximately 15 hours of flight experience.

Apparatus. The experiment was conduct in a trademark CAVE virtual environment. The CAVE was composed of four rear-projected walls and a top-projected floor. The walls and floor formed a 3.1 m cube. Alternating images were presented to each eye by synching the projection with liquid crystal shutter glasses. The virtual environment was a flat plain with surrounding mountains and hills. The plain included a textured surface with scattered trees and buildings. In addition, there was a precision runway with associated markings and airport buildings in the center of this plain. Due to the complexity of the scene the refresh rate was in the range of 20 Hz. Although not ideal, this seemed to provide an experience of smooth self-motion.

Procedure. Each trial consisted of a 30-second flight. The first ten seconds of the flight served as a preview period in which altitude and speed were constant at 600 ft and 180 kts respectively. During the next 10 s period the speed and altitude manipulations were made as indicated in Table 1. The changes were implemented gradually using an exponential function (see Patrick, 2002 for details). The numbers in parentheses in Table 1 indicate the final speed, altitude, and GOFR at the end of the 10 s period. The last 10 s period continued a level flight at the altitude and speed attained at the end of the manipulation period. When the flight was complete, the scale for entering speed judgments appeared on the screen. The observers entered their judgments using a joystick. Once speed judgments were entered, the scale for entering altitude judgments appeared and the observers entered their judgments for altitude.

Results

The data were analyzed using two 4 x 5 x 5 x 2 split plot ANOVAs. Order (4) was manipulated as a between subjects factor and Altitude Change (5), Speed Change (5), and Direction (2) were treated as within subjects factors. One ANOVA used the speed judgments as the dependent variable and the other used the altitude judgments as the dependent variable.

Speed Judgments. The ANOVA showed main effects for both Speed Change [$F_{(4,48)}=65.42$,

p<.05] and Altitude Change [F(4,48)=6.01, p<.05], but the interaction was not significant. This pattern is partly consistent with Warren's GOFR hypothesis. The effect of altitude change was in the direction predicted. For example, altitude losses led to increased judgments of speed change (i.e., more positive change or less negative change). However, as shown in Figure 2 the speed judgments were not simply proportional to GOFR. For example, note that the five cases with GOFR equal to zero, resulted in a wide range of judgments including both perceptions of increases and decreases in speed. There was also a significant interaction between Speed Change and Direction [F(4, 48)=2.79, p<.05]. The range of speed judgments was greater with the Parallel Direction. This suggests that the experience of speed change was increased when the scene had richer details provided by the runway. No other main effects were significant.

Altitude Judgments. As with speed judgments, the ANOVA showed main effects for both Altitude Change [F(4,48)=96.62, p<.05] and Speed Change [F(4,48)=2.73, p<.05], but no significant interaction. Again, the impacts of Speed Change on altitude judgment were consistent with the hypothesis that altitude judgments were influenced by GOFR. That is, increases in speed tended to be perceived as losses in altitude. However, Figure 3 shows that altitude judgments were not simply proportional to GOFR. This is consistent with the speed judgments shown in Figure 2. There was also a significant main effect for Direction [F(1,12)=8.41, p<.05]. It seems that the loss of altitude was more salient in the Parallel Direction. This might reflect the salient optical information associated with runway expansion (or splay of the runway edges).

Model

Consistent with previous studies, judgments of speed change were affected by the presence of altitude changes. The present study showed that altitude judgments were also affected by the presence of speed changes. In both cases the changes were in a direction that was consistent with the change of GOFR. Increases of GOFR were associated with increasing speed and/or decreasing altitude. Decreases of GOFR were associated with decreasing speed and/or increasing altitude. However, as shown in Figures 2 and 3 in neither case were judgments simply proportional to GOFR.

The additive relation of speed and altitude change on judgments of speed, as shown in Figure 2, is typical of results from previous studies. The primary point of contention among the studies is the relative contribution of altitude changes to the speed judgments. In a strict interpretation of Warren's GOFR hypothesis the impact of speed and altitude should be equivalent. That is, increasing speed or decreasing altitude by the same proportion should result in equivalent judgments of speed increase. Likewise, increasing speed and increasing altitude by the same proportion should cancel each other, resulting in a perception of no change in speed. In many of the studies, the impacts of altitude changes on judgments were much smaller than the impact of speed changes.
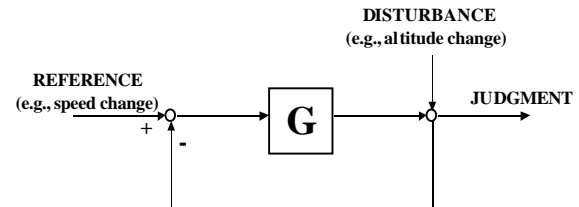

Figure 1. An observer in the form of a simple negative feedback servo.

In an attempt to reconcile the variations across the different studies, an "observer" in the form of a simple servo was evaluated. The model is illustrated in Figure 1. In this model, the signal to be judged (altitude or speed) is treated as the reference input to the observer and the other factor contributing to GOFR (speed or altitude) is treated as a disturbance. The output of this observer is the judgment of change. This output will be a joint function of both the reference (R) and the disturbance (D) mediated by the gain parameter (G).

$$\text{Judgment} = R \times [G/(1+G)] + D \times [1/(1+G)] \quad (1)$$

Figure 4 shows the predictions for two values of gain. When gain is high, the output of the observer is specific to the reference signal (the disturbance has little impact). The points linked by lines are equivalent speed changes (with varying altitude changes). The flat functions show that judgments of speed were not affected by the altitude changes. When gain is lower, the impact of the disturbance on judgments will be greater. When gain is unity the judgment will be consistent with the strong form of Warren's GOFR hypothesis – altitude and speed changes will contribute equally to judgments of speed change.. Note the high correlation between judgments and GOFR when gain was unity.
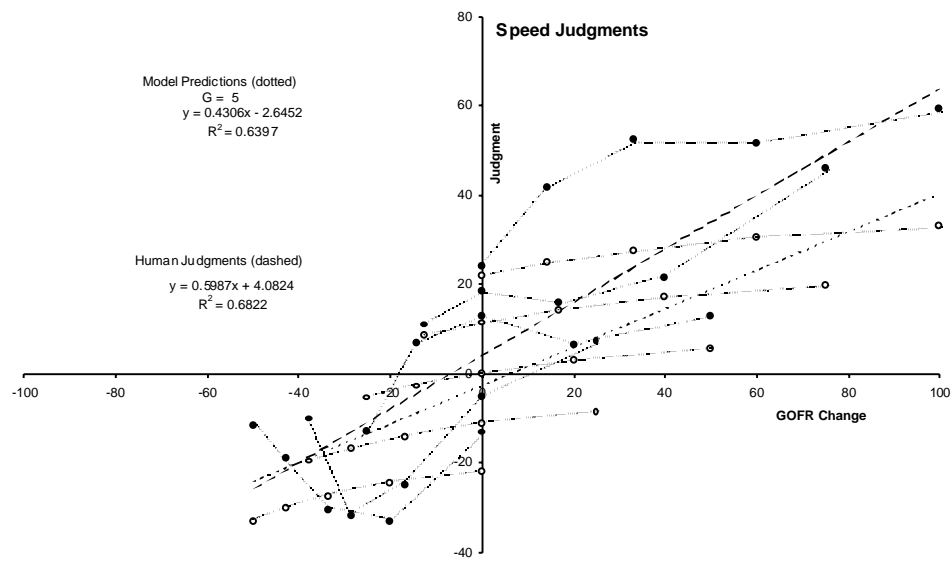
Figure 2. Speed Judgments as a function of GOF change. The filled symbols show human performance data. The open symbols show predictions of the servo model. Points linked by lines represent trials with equal changes in speed (thus, the different values of GOFR are due to altitude changes).
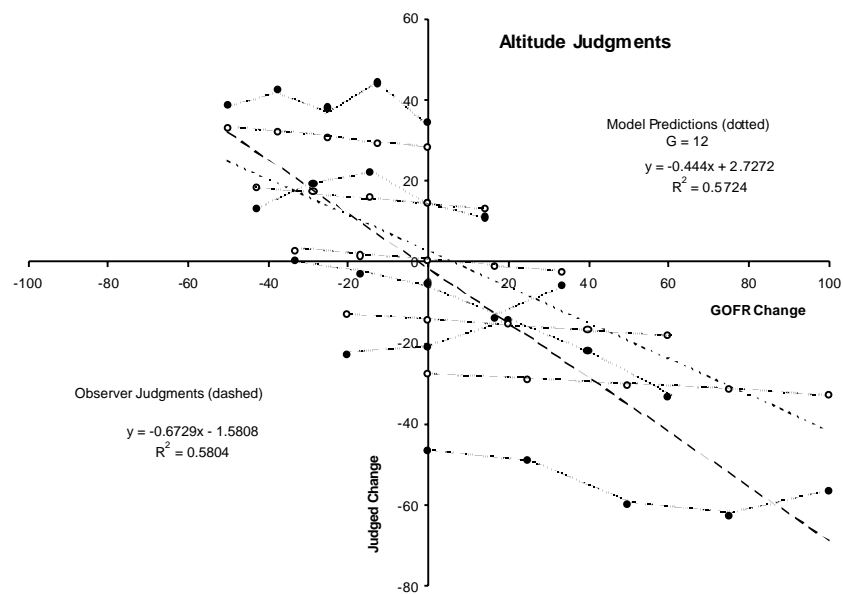

Figure 3. Altitude Judgments as a function of GOF change. The filled symbols show human performance data. The open symbols show predictions of the servo model. Points linked by lines represent trials with equal changes in altitude (thus, the different values of GOFR are due to speed changes).
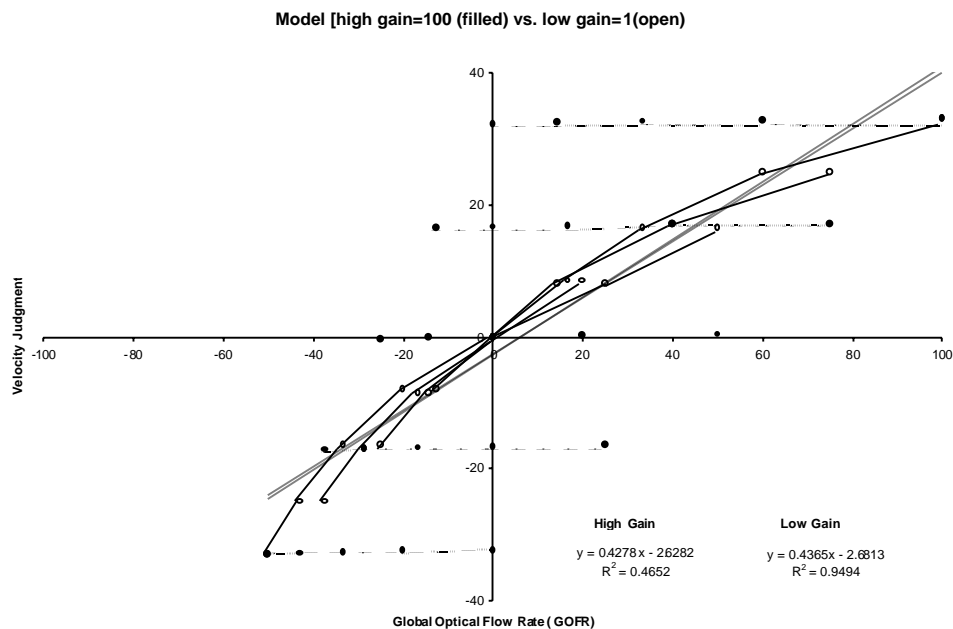
Model [high gain=100 (filled) vs. low gain=1(open)]

High Gain
y = 0.4278x - 2.6282
R^2 = 0.4652

Low Gain
y = 0.4365x - 2.6813
R^2 = 0.9494

Velocity Judgment

Global Optical Flow Rate (GOFR)

Figure 4. Predictions of speed judgments using the servo model. When G is high (filled symbols) judgments are specific to speed change with little influence due to altitude change. When G is low (open symbols) judgments are affected equally by speed and altitude change as predicted by Warren's GOFR hypothesis.. Points linked by lines are equivalent speed changes (with different degrees of altitude change).

It is important to note that the model in Figure 1 is not a "process" model of the observation task. It is simply an analytic formalism that allows a single parameter (G) to quantify a range of possible ways that altitude and speed might jointly contribute to judgments of either speed or altitude. By changing the value of G it is possible to vary the nature of the additive effects of the two components of GOFR on either speed or altitude judgments.

Summary and Conclusions

Many of the studies of the GOFR hypothesis were framed to determine what single property of the optical flow field is "causing" the speed judgments. For example, Larish and Flach (1990) pitted GOFR against edge rate. They found significant but small effects of altitude (GOFR) on speed judgments. They concluded that "edge rate" was the dominant optical variable determining speed judgments. Dyer (1997) on the other hand, found that GOFR dominated "discontinuity rate" in determining judgments about change in speed. Essentially all the empirical results reported in the literature fall somewhere between the two extremes shown in Figure 4. That is, the results typically show additive effects of altitude and speed

change on judgments of speed. However, the size of the impact of altitude changes relative to the size of the impact of speed changes has varied widely across the studies.

The servo model suggests a weaker form of the GOFR hypothesis. That is, that GOFR is one of multiple factors contributing to speed and altitude judgments. The G parameter then becomes an index for quantifying the contributions of these other factors to disambiguating the unique contributions of speed or altitude to judgments. For example, other properties of an optical flow event, such as regularly spaced edges or discontinuities, well specified splay angles, objects of known size, etc. may help observers to differentiate altitude and speed changes. When there is rich information, then the observer should behave like a "well-tuned" observer (high gain) and perceptions should be specific to the reference that is to be judged (either speed or altitude). When the information field is less rich, then the observer will likely have more difficulty tuning in to the reference signal and the judgments should reflect influences of any disturbances that might be present. In this case, the observer would have low gain.

This suggests that research should be framed to explore the possible interactions among many potential sources of information that might make it easier or harder to "tune" into altitude and speed changes. In terms of aviation safety, the issue becomes one of identifying natural situations where the information may be inadequate to disambiguate between changes in altitude and speed.

In conclusion, it seems clear that altitude changes can influence speed judgments. Similarly, speed changes can influence altitude judgments. However, the degree of influence may depend on other properties of the optical flow event. Future research should be framed to consider the many possible factors that may determine the functional value of gain (G) for the human observer.

References

Ballard, T.G. Roach, T. & Dyre, B.P. (1998). Use of global optical flow rates depends on their validity as determinants of egospeed. *Proceedings of the 42nd Annual Meeting of the Human Factors and Ergonomics Society*, 2, 1440-1444.

Dyre, B.P. (1997). Perception of accelerating self-motion: Global optical flow rate dominates discontinuity rate. *Proceedings of the 41st Annual Meeting of the Human Factors and Ergonomics Society,* 2, 1333-1337.

Gibson, J.J., Olum, P.., & Rosenblatt, F. (1955). Parallax and the perspective during aircraft landings. *American Journal of Psychology*, 68, 372-385.

Flach, J.M., Hagen, B.A., Larish, J.F. (1992). Active regulation of altitude as a function of optical texture. *Perception & Psychophysics*, 51, 557-568.

Flach, J.M., Warren, R., Garness, S.A., Kelly, L., & Stanard, T. (1997). Perception and control of altitude: Splay and depression angles. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 1 – 19/

Larish, J.F. & Flach, J.M. (1990). Sources of optical information useful for the perception of speed of rectilinear self-motion. *Journal of Experimental Psychology: Human Perception and Performance,* 16, 295 – 302.

Owen, D.H. & Warren, R. (1987). Perception and control of self-motion: Implications for visual simulation of vehicular locomotion. In L.S. Mark, J.S. Warm, & R.L. Huston (Eds.) *Ergonomics and human factors: Recent research.* (pp. 40-70). New York: Springer-Verlag.

Owen, D.H. Warren, R., Jensen, R.S., Mangold, S.J., & Hettinger, L.J. (1981). Optical information for detecting loss in one's own forward speed. *Acta Psychologica*, 48, 203-213.

Patrick, D.L. (2002). On judging height and speed: Global optical flow. Unpublished Master Thesis. Wright State University, Dayton, OH.

Warren, R. (1982). *Optical transformations during movement: review of the optical concomitants of egomotion.* (NTIS Tech Rep. No. AD-A122275). Columbus, OH: Ohio State University, Department of Psychology.